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METROLOGY FOR X-RAY TELESCOPE MIRRORS IN A VERTICAL CONFIGURATION*

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Abstract

Mirrors used in x-ray telescope systems for observations outside of the earth's atmosphere are usually made of several thin nested shells, each formed by a pair of paraboloidal and hyperboloidal surfaces. The thin shells are very susceptible to self-weight deflection caused by gravity and are nearly impossible to test by conventional interferometric techniques. The metrology requirements for these mirrors are extremely challenging. This paper presents a prototype of a Vertical Scanning Long Trace Profiler (VSLTP) which is optimized to measure the surface figure of x-ray telescope mirrors in a vertical orientation. The optical system of the VSLTP is described. Experimental results from measurements on an x-ray telescope mandrel and tests of the accuracy and repeatability of the prototype VSLTP are presented. The prototype instrument has achieved a height measurement accuracy of about 50 nanometers with a repeatability of better than 20 nanometers, and a slope measurement accuracy of about 1 microradian.

Introduction

X-ray telescope optics, such as for the Advanced X-ray Astrophysics Facility (AXAF), are often made of a series of nested shells[1,2], each of them in the shape of a pair of paraboloids and hyperboloids with long axial radii of curvature (typically hundreds of meters) and short sagittal radii (from 10 to 100 cm), as shown in Figure 1. They are nearly impossible to test by conventional interferometric techniques.

The standard test for x-ray telescope performance is the encircled energy measurement, where a point source of x-rays is imaged by the mirror onto a suitable detector. Such a test requires an elaborate facility to provide a vacuum environment for the x-ray source and optical element under test. It does not provide a direct measurement of the surface figure of the mirror, rather the suspect errors must be inferred from the integrated intensity measurement. It is not easy to provide feedback to the fabrication process with this kind of a measurement technique.

Other metrology techniques have been developed for specific x-ray telescope programs to measure the shape of the surface directly. As an example, the AXAF mirror fabrication program uses a Fizeau type fringe scanning system to measure the tangential shape of each of the glass shells use in the nested Wolter I telescope system [2]. The fringe scanning system requires a set of precisely calibrated cylindrical or toroidal test surfaces to use to generate the fringes recorded in the measurement.
Calibrating and certifying the shape of each auxiliary test surface is in itself a major metrology effort and is not a cost-effective technique for the production of typical SR optics by small shops or as a quality assurance tool by the end user for acceptance testing of the final delivered optic.

The Long Trace Profilometer (LTP) was originally developed at Brookhaven National Laboratory (BNL) to measure the surface figure of cylindrical aspheres used

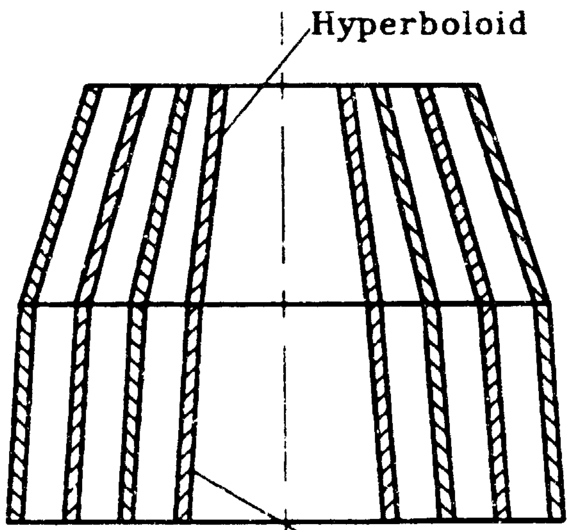


Fig. 1 - A cross section view of an x-ray telescope comprised of several thin nested shells.

to reflect x-rays in Synchrotron Radiation (SR) beam lines.[3-6] Based on the principle of the pencil beam interferometer originally developed by von Bieren[7, 8], the LTP is optimized to measure the figure errors and mid-frequency slope errors on highly astigmatic surfaces, i.e. those with an extremely long radius of curvature in the tangential direction (hundreds of meters to several kilometers) and with a sagittal radius as small as 1 centimeter. These surfaces are usually made in the shape of far off-axis segments of paraboloids, hyperboloids, and ellipsoids, or as toroids or cylinders that are bent into the proper tangential radius. Conventional metrology on such exotic surface shapes is not possible. Hence the need for a versatile scanning profiler capable of handling a variety of shapes and sizes up to 1 meter in length.

The main advantage of the LTP over similar non-contact measuring machines is that it does not use any auxiliary reference surfaces that need to be calibrated and matched to the surface under test. It can be easily configured to measure a wide range of surface figures on grazing incidence optics. A reference beam is used to monitor errors in the motion of the optical head as it traverses the air bearing slide. Removal of the error signal from the test signal results in an absolute measurement of the surface slope, without the need to use expensive calibrated reference surfaces. Because of this versatility, a number of SR facilities expressed an interest in acquiring their own LTP instrument to use as a quality assurance tool, and a commercial version (LTP II) of the original instrument was developed as a result of a collaboration between BNL, Lawrence Berkeley Laboratory and Continental Optical Corporation.

The mirrors used in the AXAF telescope are similar to SR mirrors in surface shape, size, and requirements. In fact, SR mirrors can be thought as being a small segment of an AXAF-type mirror. Testing AXAF mirrors usually requires a full 3D map of errors for surface slope and height. Under the NASA sponsored SBIR project, Continental developed a prototype Vertical Scanning Long Trace Profiler (VSLTP) which is capable of measuring the complete surface figure of x-ray telescope mirrors in a 3D manner. The following sections describe the configuration of the VSLTP optical system and present some of the results from the Phase I project. We successfully demonstrated the feasibility of using the LTP to measure the figure and mid-frequency slope errors on x-ray telescope optics and to provide a 3D scan capability for mapping the surfaces of complete cylinders.

Optical System Description

A schematic view of the prototype VSLTP optical system is shown in Figure 2. The components inside the dashed lines are from a standard Long Trace Profiler (LTP II) optical head.[3, 4] A beam from a polarized HeNe laser (not shown) is launched into a polarization-preserving fiber. The collimated beam exiting the fiber first goes through a variable attenuator, which preserves the linear polarization direction, and then enters the non-polarizing cube beamsplitter. The single beam is split into two equal components, which then go through separate Porro prisms and then return back into the cube beamsplitter. One of the prisms is adjustable in the transverse direction, which provides lateral displacement between the two beams while maintaining their exact colinearity. The standard measurement configuration is to separate the beams by about 1 mm, which is approximately one laser beam diameter. This provides the optimum sampling configuration for scanning the surface.

After exiting the first beamsplitter, the probe beam pair goes first through a half-wave rotation plate, and then through a polarizing beamsplitter cube. This cube splits the beam pair again into two sets, one set exits the cube vertically and is directed toward a small flat reference mirror, the other exits horizontally to hit the surface under test. These beams are nominally circularly polarized after exiting the polarizing cube which has 1/4 wave plates attached to the exit faces. The intensity between the two beams is adjusted by rotating the half-wave plate to obtain equal intensity in the test and reference fringe patterns. The relative intensity between the two beams will need to be adjusted depending on the reflectivity of the surface under test. Both probe beam pairs return upon reflection to pass back through the polarizing cube, and are then brought to separate focus points on the detector, via a Fourier transform lens. Within each focal spot a fringe pattern is produced by interference between the two components of each beam pair. The interference patterns are recorded by a linear photodiode array, and the positions of the minima in each pattern provide information about the local surface slope of the test and reference surface.

The standard LTP II system scans the surface of a SR mirror in a horizontal direction along a meridional line of symmetry. For AXAF mirrors, a 3D mapping of the surface is desired. The critical steps in 3D scanning are: scanning vertically along a number of meridians,

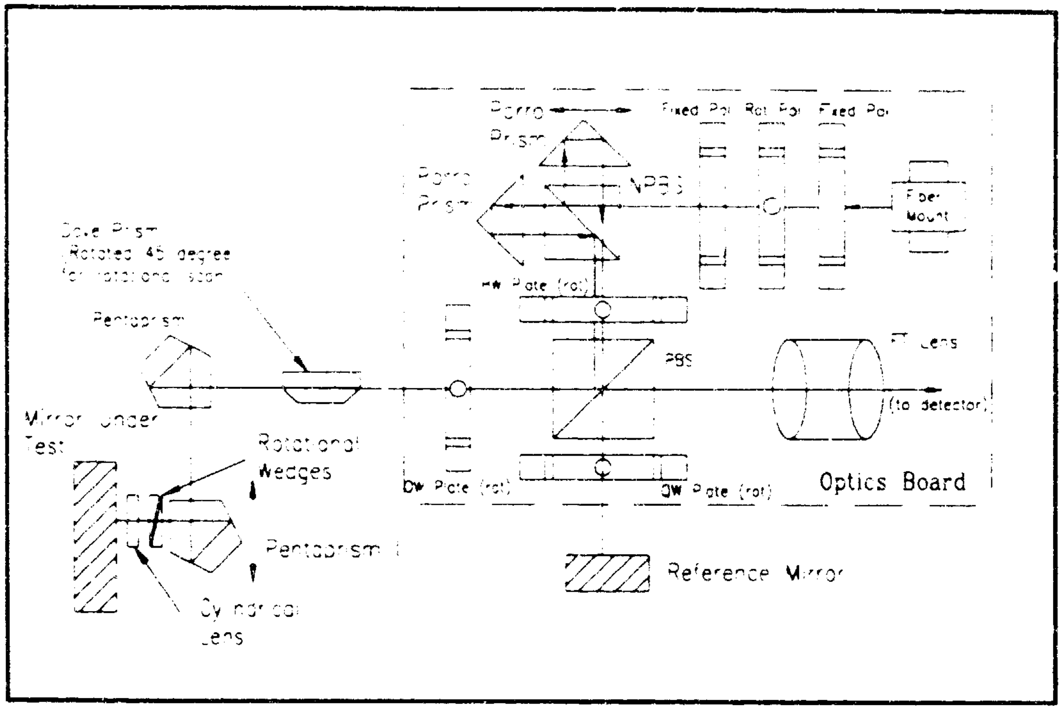


Fig. 2 - Schematic diagram of the VSLTP optical system. Items enclosed within the dashed box are standard LTP II optical head components.

scanning in azimuth at several fixed meridional distances, and combining the results from these two directions into a single view of the surface. A number of additions and modifications were made to the standard LTP II optical system to accommodate 3D mapping requirements. The major change was to make the optical head stationary and use penta prisms to direct the beam onto the test surface. The original pencil beam interferometer by von Bieren[5, 6] used a penta prism for this same purpose. Qian, et al.[9] have demonstrated that improvem- nts in the precision and accuracy of the measurement are possible with this configuration. A pair of penta prisms was mounted onto a linear translation stage, one fixed to the frame, the other movable on the slider, to allow the laser beam to be directed at right angles onto the mirror surface while being scanned in the vertical direction.

Another modification was required to accommodate the cone angle of the telescope segment. Since telescope mirrors are really conical in shape, rather than right cylinders, and the vertical translation stage is constrained to move exactly along the direction of the mirror symmetry axis, a means of offsetting the direction of the probe beam exiting the moving penta prism is necessary to make the reflected beam return through the optical system. The acceptance angle of the standard LTP II system is ±5 mrads about its optical axis, but the cone angle of a typical telescope mirror is about a few degrees. A pair of adjustable Risley prisms was added after the moving penta prism to permit the beam to be directed toward the normal to the tilted surface. This adjustment allows one to add a bias into the direction of the probe beam without sacrificing any precision or accuracy in the measurement. The return beam thus remains centered on the detector and utilizes the entire dynamic range of the system.

The LTP II normally scans along one line in the meridional direction along the direction of the symmetry axis of the mirror. In order to map the entire surface in 3D, it is necessary to scan the VSLTP along a number of meridians spaced equally in azimuth. In order to completely define the surface shape, it is necessary to tie all of the meridional scans together with a series of azimuthal scans.[1] In order to make azimuthal scans with the LTP, it is necessary to rotate the orientation of the separation vector between the two components of the test arm beam so they lie in the azimuthal direction, not in the meridional direction. The direction of separation must always be along the direction of the scan. A Dove prism rotated about its optical axis by 45 degrees produces the required 90 degree beam rotation. Upon returning into the optical head after reflection from the test surface, the beam pair is rotated back to its original orientation. The interference fringes on the detector are again oriented in the proper direction, even though the probe beam pair is rotated by 90 degrees on the test surface.

Experimental Results

To demonstrate the feasibility of using the LTP technique to measure x-ray telescope surfaces in 3D in the vertical orientation, we performed a proof-of-concept experiment. A test surface was provided to us by NASA/MSFC, which consisted of a polished mandrel in the shape of a Wolter I telescope. The mandrel consists of two segments - a paraboloid and an hyperboloid, each 47.5 mm long - that are part of the same substrate. A series of scans was made in both the meridional and azimuthal directions and a 3D map of the surface height topography was generated from the individual slope measurements.

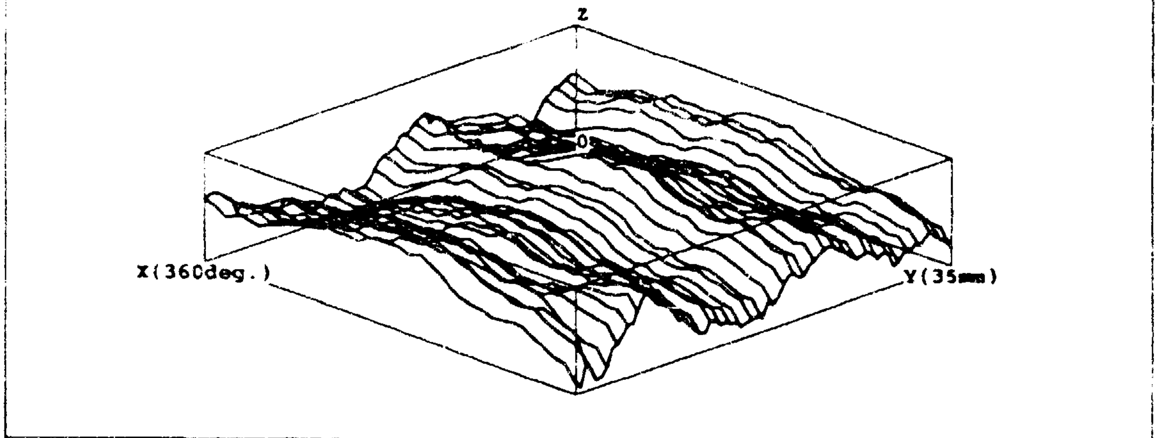
A complete set of scans is accomplished in two steps: first a set of scans is made in the vertical (meridional) direction, then a set of scans is made in the azimuthal direction. For the vertical scans, the pencil beam pair is oriented in the vertical direction, parallel to the direction of the scan. For the NASA mandrel, a total of 37 vertical scans were made on the paraboloid segment at 10 degree intervals in azimuth. Each vertical scan is comprised of 35 data points separated by 1 mm intervals in the vertical z-direction. Immediately following the set of vertical scans, a series of azimuthal scans is made at several vertical height positions. Before the azimuthal scans can be made, the Dove prism is rotated by 45 degrees to orient the test beam pair in the azimuthal direction. Six scans are made along the 35 mm height of the paraboloid segment, each separated by 7 mm in the vertical direction. Each azimuthal scan is comprised of 73 data points taken at 5 degree increments in azimuth.

In order to generate a 3D wire-frame map of the surface topography, it is necessary to correlate the azimuthal scans with the meridional scans. The meridional profiles contain the tangential surface curvature and higher order topography information, but their endpoints are not tied to the proper height values. The azimuthal scans are needed to tie the endpoints of the meridional scans together. The azimuthal scans, however, provide information only about the departure of the surface from some ideal average radius. Unlike the meridional scans, we lose information about the absolute surface curvature when we make a rotary scan in the azimuthal direction with a slope-measuring interferometer. However, if we are only interested in the departure of the surface from some best-fit ideal cylinder, then it is sufficient to convert the azimuthal slope profiles to residual height profiles by simple integration after the mean has been subtracted from each. For purposes of simplicity, we used only the top and bottom azimuthal scans to pin the endpoints of each meridional scan. When we do this, we get the departure of the measured surface from some best-fit cone.

We then go one step further in the analysis by subtracting the desired paraboloidal shape from each of the meridional scans, using the theoretical parameters for the telescope prescription. These results are shown in Fig. 3, which represents the departure of the surface from the desired ideal conic section. The results indicate a peak-to valley departure of the surface from the ideal of about 0.32 microns, or about 1/2 wave at the HeNe wavelength.

Finally, we did tests on the repeatability and accuracy of the prototype VSLTP. An estimation of measurement repeatability was made by making a series of vertical and rotational scans on the mandrel. Three sets of 37 vertical scans were made consecutively, and then 3 sets of 6 azimuthal scans were made, also consecutively. This pattern was chosen so as to produce minimum system disturbance by operator intervention and to minimize the need to realign the probe beam after rotating the Dove prism. Residual surface height profiles were generated by combining the vertical and azimuthal data sets in 9 different ways. The average RMS value of the differences between these data sets taken in pairs is on the order of 20 nanometers. Although this number indicates excellent repeatability, we are confident that this number can easily be reduced by proper instrument design and better environmental control during the measurement.

The ability of the VSLTP to measure absolute radius of curvature was tested by measuring the shape of two spherical test plates of known radius. Test plates with known radii of 4.0197 m and 1.0282 m were measured by both the standard LTP II and by the VSLTP prototype. We found that errors of radius estimation for both the LTP II and VSLTP were less than 0.1 % in all cases, which results in a sag error of about 50 nanometers. The accuracy in measuring RMS slope



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Ymin:	0.000000	**Ymax:**	35.000000	**Y Unit:**	mm
Zmin:	-9.291898e-005	**Zmax:**	2.288191e-004	**Z Unit:**	Height(mm)

Fig. 3 - An unfolded 3D view of the residual surface showing the departure of the mandrel surface from the ideal paraboloid.

errors was also tested by comparing measurements made on several test plates with both instruments. The results indicate that, for surfaces with RMS residual slope errors in the range of several microradians, the present VSLTP is consistently higher by about 1 microradian. This is not unexpected, since the entire mount and structure of the bridge and vertical scanning stage is not optimized for maximum stability. Despite the non-optimum nature of the prototype system, the VSLTP can now provide measurements with an accuracy of 0.2 arc-second and about 0.1 wavelength or 50 nanometers for the slope and height, respectively.

Cylindrical Compensation Lens Design

One problem in designing the VSLTP optical system is the need for two kinds of cylinder lenses in front of the Risley prisms. In the standard LTP system, when measuring cylindrical surfaces or other conicoids (toroids, ellipsoids, and paraboloids), a cylindrical lens oriented with its symmetry axis parallel to the test surface axis is needed to compensate for the defocusing effect of the transverse curvature. The focal point of the cylindrical lens is usually located at the mirror surface under test, which is the "cat's eye" configuration. However, the design of the cylindrical lens in VSLTP has to follow other criteria. The cylinder lens needs to be chosen so that the wavefront curvature in the azimuthal direction matches the concave or convex curvature of the mirror shell or mandrel. The cylinder lens needs to have a positive power for convex surfaces (mandrels) and a negative power for concave surfaces (shells). The proper cylinder lens provides the proper beam pair separation of the wavefronts on the surface necessary for interference fringe formation on the detector, whereas the cat's eye configuration would produce no interference in the azimuthal direction. The distance from the cylinder lens to the surface and to the symmetry axis of the part are now a critical parameters. In our experiments, the focal length of the positive cylindrical lens is about 40 mm longer than radius of the mandrel thus leaving some space between the lens and the mirror surface for mechanical components. For measuring the shell mirror, focal length of the negative cylindrical lens was chosen to be about 40 mm shorter than the internal radius of the shell. This design makes the separation of the two beam spots in the azimuthal direction slightly smaller than 1 mm on the mandrel mirror surface and slightly larger than 1 mm on the shell surface.

Errors Introduced by Mechanical Noise of the Rotary Table

We found that the system errors for the data obtained in the azimuthal direction become larger when the weight of the mirrors and its supports exceeds the capacity of the rotational stage. In this case, height data from the azimuthal scan contains a significant noise signal with frequency components higher than the fundamental. This makes the procedure of subtracting the rigid body alignment errors to find the true surface deformation very difficult. In the current algorithm, we assume that the tilt and eccentricity of the part on the rotary stage will only appear in the integrated height curve at the fundamental frequency. An simple optimization program was written to fit a sinusoid to the data by least square minimization. After subtracting the fit curve, the residual is taken as the surface deviation from the ideal cone as mentioned in the previous section. Another possible approach is to do Fourier transform and subtract component of the fundamental frequency in the frequency domain. We found that the first method results in better estimation. However, when the mechanical noise level of the rotary stage is too high or the alignment of the part to the rotation axis is not good, both methods will not work well.

Conclusion

Experiments mentioned above have demonstrated that the VSLTP is capable of making 3D non-contact measurements of the shape of x-ray telescope mirrors in the vertical orientation with errors as small as nanometers in height or at the microradian level in slope. In comparing with previous metrology techniques for x-ray astronomy optics, which have utilized contact profilometry, the current method puts the surface at no risk of being damaged. Other techniques using x-ray sources and long vacuum tunnels can only measure components in a horizontal configuration and only give overall performance quality numbers. The VSLTP technique presents an ideal solution for manufacturing and testing of the mirrors used in x-ray projects.

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